

NASA's Research in Aircraft Vulnerability Mitigation

Cheryl L. Allen¹

NASA Langley Research Center, Hampton, VA 23681

Since its inception in 1958, the National Aeronautics and Space Administration's (NASA) role in civil aeronautics has been to develop high-risk, high-payoff technologies to meet critical national aviation challenges. Following the events of Sept. 11, 2001, NASA recognized that it now shared the responsibility for improving homeland security. The NASA Strategic Plan was modified to include requirements to enable a more secure air transportation system by investing in technologies and collaborating with other agencies, industry, and academia. NASA is conducting research to develop and advance innovative and commercially viable technologies that will reduce the vulnerability of aircraft to threats or hostile actions, and identify and inform users of potential vulnerabilities in a timely manner. Presented in this paper are research plans and preliminary status for mitigating the effects of damage due to direct attacks on civil transport aircraft. The NASA approach to mitigation includes: preventing loss of an aircraft due to a hit from man-portable air defense systems; developing fuel system technologies that prevent or minimize in-flight vulnerability to small arms or other projectiles; providing protection from electromagnetic energy attacks by detecting directed energy threats to aircraft and on/off-board systems; and minimizing the damage due to high-energy attacks (explosions and fire) by developing advanced lightweight, damage-resistant composites and structural concepts. An approach to preventing aircraft from being used as weapons of mass destruction will also be discussed.

ACRONYMS

AirSTAR	Airborne Subscale Transport Aircraft Research
AFRL	Air Force Research Lab
ARC	Ames Research Center
ARIES	Airborne Research Integrated Experiments System
ARMD	Aeronautics Research Mission Directorate
A&SVM	Aircraft and Systems Vulnerability Mitigation
AvSSP	Aviation Safety and Security Program
CEM	Computational Electromagnetics Modeling
CNS	Communication/Navigation/Surveillance
ConOps	Concept of Operations
COTS	Commercial Off-the-Shelf
DACS	Damage Adaptive Control System
DFRC	Dryden Flight Research Center
DHS	Department of Homeland Security
DoD	Department of Defense
E-AGCAS	Enhanced Auto Ground Collision Avoidance System
EGPWS	Enhanced Ground Proximity Warning System
EME	Electromagnetic Effects
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
FAA	Federal Aviation Administration
FRDTC	Fire Resistant, High Damage Tolerant Composites
FTEP	Fuel Tank Explosion Protection

¹ Project Manager, Aircraft & Systems Vulnerability Mitigation Project, Aviation Safety and Security Program, Mail Stop 229, Hampton, VA 23681.

GRC	Glenn Research Center
HIRF	High Intensity Radiated Fields
HPM	High Power Microwave
IR	Infrared
LaRC	Langley Research Center
MANPADS	Man-Portable Air-Defense Systems
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
PAFS	Protected Asset Flight System
RF	Radio Frequency
SAFR	Secure Aircraft Flight Recovery
SASIF	Secure Aircraft System for Information Flow
SAFETI	Systems and Airframe Failure Emulation Testing and Integration
SVD	System Vulnerability Detection
TCAS	Traffic Alert/Collision Avoidance System
TFR	Temporary Flight Restriction
TSA	Transportation Security Agency
TAWS	Awareness and Warning Systems

I. Introduction

In the preface to the National Strategy for Homeland Security¹, July 16, 2002, President George W. Bush states, “The U.S. government has no more important mission than protecting the homeland from future terrorist attacks,” and that “We must rally our entire society to overcome a new and very complex challenge. Homeland security is a shared responsibility.” NASA responded to this challenge by creating new projects within its Aviation Safety and Security Program that seek to develop technologies to address the security needs of the current and future national air transportation system. Since its inception, NASA’s long-range research and development capabilities have provided advances in all areas of aviation, so, as noted by NASA Administrator Sean O’Keefe in NASA 2003 Strategic Plan²: “The increasingly complex and dangerous international arena compels us to aggressively apply our expertise and technologies to improve homeland security.”

Within its Aeronautics Research Mission Directorate (ARMD), NASA’s objectives are to protect air travelers and the public, protect the environment, increase mobility, and explore new aeronautical missions. To meet these objectives, programs have been established to develop technologies for new or advanced vehicle concepts, to reduce emissions and noise, to increase the national airspace system capacity, and to minimize accidents. New projects to provide technology to help reduce vulnerability to hostile acts, both directly for aircraft as well as throughout the air transportation system, are a combination of an extension of similar work being applied to the problems of safety and investments in areas that are relatively new to NASA. All initiatives are worked in close collaboration with other agencies, including the Department of Defense (DoD), the Department of Homeland Security (DHS), the Transportation Security Agency (TSA), and the Federal Aviation Administration (FAA).

II. Overview of Aviation Safety & Security Program

The objective of NASA’s Aviation Safety and Security Program (AvSSP) is to develop technologies that enable a reduction in the commercial aviation accident rate, increase the robustness of national air transportation system, and identify potential vulnerabilities. While the goal of NASA’s Safety research is to prevent unintentional life-threatening events, Security research investments look to stop intrusions into the system that are intended to cause damage, harm, and loss of life. Security research in AvSSP will develop concepts and technologies that reduce the vulnerability of the aviation system to criminal and terrorist attacks while dramatically improving the efficiency of such protection.

NASA’s approach is to work with members of the aviation community (developers, operators, regulators, users, etc) to identify threats, mitigate effects of hostile acts, and qualify and transfer technologies for a robust system and infrastructure. AvSSP focuses primarily on security technologies for commercial and general aviation aircraft that have a long-term development horizon. Consideration is given to security requirements as part of an integrated system that must also meet safety, capacity, and mobility requirements.

AvSSP focuses on five general application areas: securing and protecting the aircraft, securing vehicle Communication/Navigation/Surveillance (CNS) systems, harden the National Airspace System (NAS), increase effectiveness of information screening, and integrate advanced sensors into aircraft. The organizational chart for

AvSSP can be seen in Figure 1. The three security-focused projects include: the Secure Aircraft Systems for Information Flow (SASIF) project, responsible for securing aircraft communications and network systems; the System Vulnerability Detection (SVD) project, responsible for system vulnerability discovery and management; and, the Aircraft & Systems Vulnerability Mitigation (A&SVM) project, responsible for hostile act intervention and prevention.

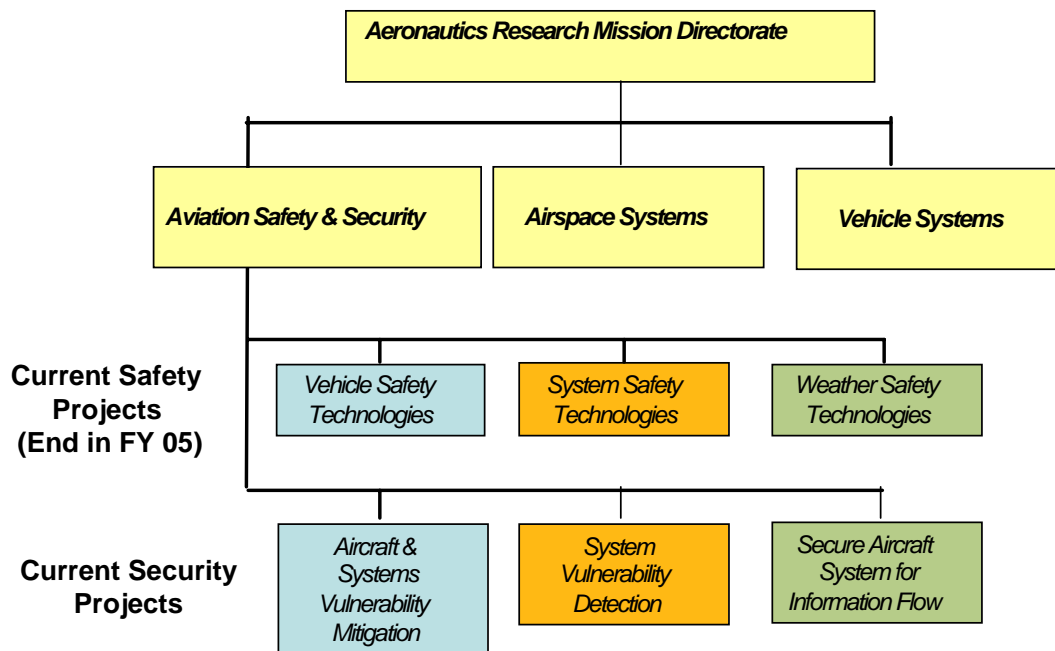


Figure 1. AvSSP Organizational Chart

The goal of SASIF is to secure aircraft networks and communication links from intentional threats, enable surveillance of aircraft, and minimize protected airspace intrusions. Solutions being addressed begin with hardened onboard aircraft systems, but also include hardening the airspace system. Cyber threats have increased along with the rapid increase of datalink and information technologies in the aircraft and the NAS. SASIF technologies will help protect air travelers by ensuring that CNS systems on aircraft cannot be compromised.

The majority of AvSSP resources for security-related research are expended on hardening and vulnerability reduction. However, the identification of new and emerging vulnerabilities is important to decision-makers who react to those threats, as well as to researchers who develop prevention and mitigation technologies. Furthermore, many threats exist beyond the realm of the aircraft, within the airspace system and in airports. SVD leverages capabilities in several key areas where vulnerabilities within the system can be detected, and advances technologies that detect and inform users of potential security vulnerabilities.

NASA's research efforts specific to aircraft vulnerability mitigation are conducted primarily within the A&SVM project, and will therefore become the focus for the remainder of this paper.

III. Aircraft & Systems Vulnerability Mitigation Project

The objective of A&SVM is to develop and advance technologies that will mitigate consequences to the aircraft from an intentional attack, with the focus of the research efforts being the aircraft itself. Since those with malicious intent will continue to find ways to successfully carry out attacks, effectively dealing with the consequences is a critical component in protecting users of the commercial air transportation system. Through coordinated research activities at Langley, Glenn, Dryden, and Ames Research Centers, the A&SVM will demonstrate and deliver vehicle-based technologies that are designed to maximize the robustness of aircraft systems while addressing human behavior and decision-making requirements. Specifically, the project will:

- Demonstrate and evaluate technologies & methods to provide accurate information to enable pilot avoidance of protected airspace, maintain positive identity verification, and deny flight control access to unauthorized persons.
- Evaluate concepts for the ability to recover a seized aircraft safely to landing.
- Demonstrate on-board and ground surveillance & interception systems for aircraft immunity to electromagnetic interference (EMI) & electromagnetic pulse (EMP) intrusions.
- Demonstrate and evaluate flight control systems that accommodate damaged control surfaces and changes to aircraft stability and control characteristics.
- Evaluate fuel system technologies that prevent or minimize in-flight vulnerability of civil transport aircraft fuel tanks due to small arms or man-portable air defense systems type projectiles.
- Evaluate material systems and fuselage structural concepts that are resistant to fire and explosions.

The products are primarily intended for next-generation aircraft; however, issues such as retrofit, certification, system implementation, and cost-benefit analysis are considered during the technology development process.

Six sub-projects define in the A&SVM investment area (see Fig. 2): Protected Asset Flight System (PAFS); Secure Aircraft Flight Recovery (SAFR); Electromagnetic Effects (EME) Surveillance and Detection; Damage Adaptive Control System (DACS); Fire Resistant, High Damage Tolerant Composites (FRDTC); and Fuel Tank Explosion Protection (FTEP).

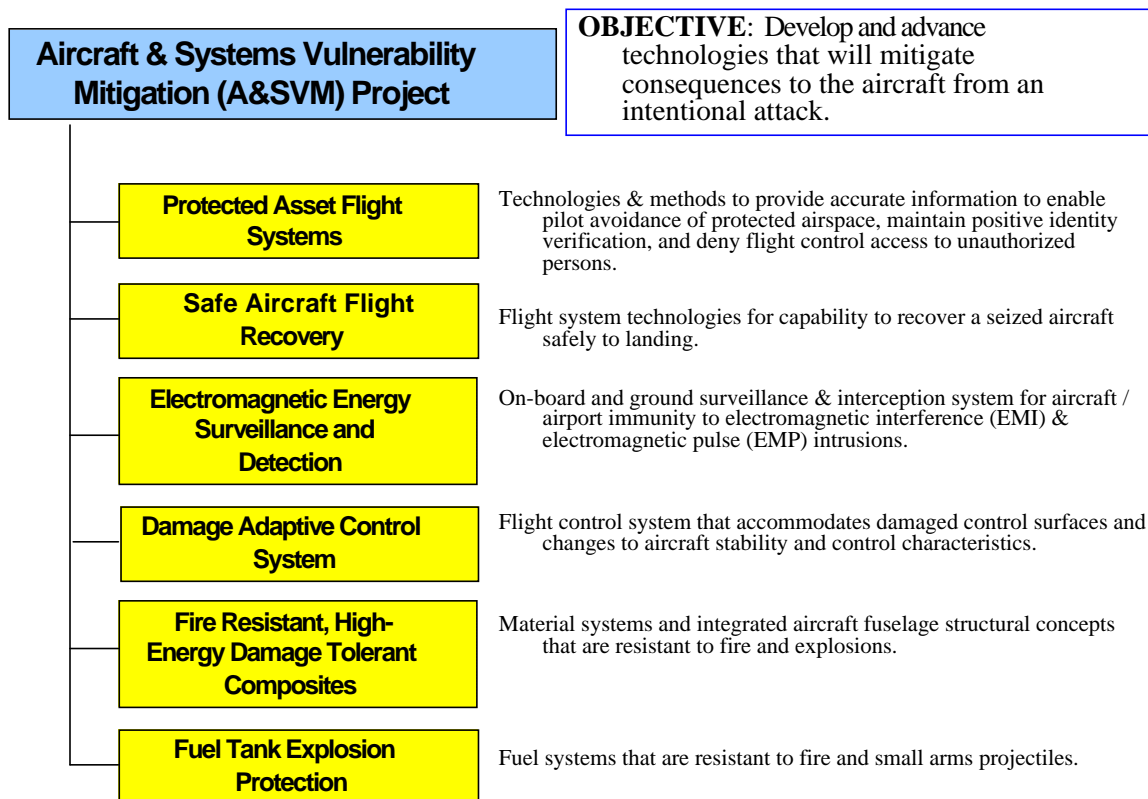


Figure 2. A&SVM Project Breakdown

The remainder of this paper will describe each sub-project in detail, providing research status where possible.

IV. Protected Asset Flight System

The PAFS sub-project is focused on reducing the likelihood that hijacked aircraft are used as weapons, while protecting both aircraft and occupants. While much has been done to limit access of aircraft to terrorists, there are few options once an unauthorized pilot gains control. Mr. Stephen McHale, Deputy Administrator of the TSA stated in November, 2003, “Terrorists will continue to consider attacks against commercial aircraft in the United States and abroad, intending to employ suicide hijackings and bombings as the most promising methods to destroy aircraft in flight, as well as to strike ground targets”. Therefore, there exists a need to identify to controlling agencies and other members of the NAS when authorized pilots are no longer operating an aircraft for an authorized purpose, and trigger a transition to a more secure mode of an onboard crash avoidance system, potentially one that could not be overridden by the pilot. The identification of actions taken against an aircraft considered a threat require a high degree of accuracy in the threat determination, and therefore making this determination will require input from several different sensor types that can be fused by a decision making process.

The objectives of the PAFS sub-project are to: develop requirements and methods for establishing, using, and distributing aircraft threat level information (“hostile” or “friendly”), possibly including the use of biometric technologies; develop and evaluate technologies for on-board flight systems to prevent unintentional incursions into protected airspace and intentional hostile activities (e.g. flying into terrain, man-made structures, or other air vehicles); and establish the operational requirements, concepts, and processes necessary to integrate these with the aircrew, aircraft systems, and the airspace system.

The PAFS technical approach is shown in Figure 3. Technologies in areas of interest include: biometric identification; video surveillance, storage, and transmission; proximity and direct access control; acoustic monitoring and analysis; intent determination; airborne transponders; Radio Frequency Identification; integrated cockpit avionics and displays, collision avoidance systems such as, weather avoidance systems, and Traffic Alert/Collision Avoidance System (TCAS); collision detection sensors; flight management and control systems; and flight maneuver monitoring, analysis, and limitation; and airborne data link.

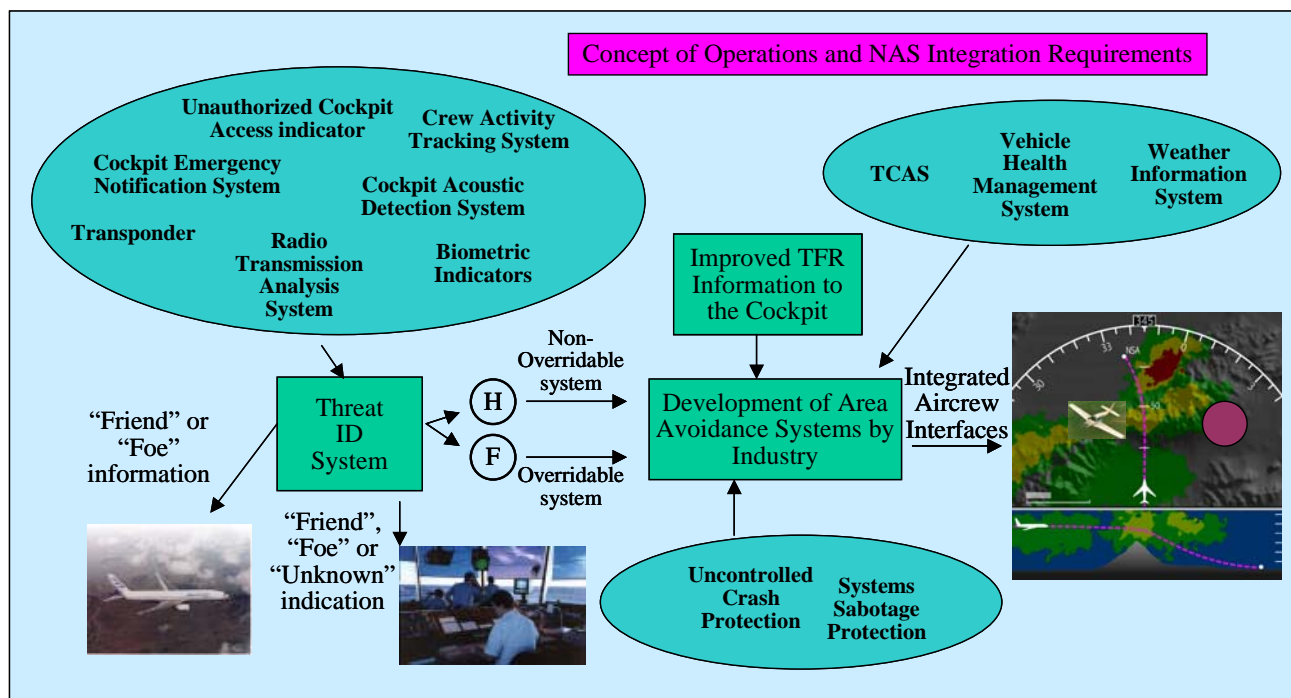


Figure 3. PAFS Technical Approach

The activities planned for the PAFS sub-project are to develop the documentation to support secure flight system concept research (ConOps, system and sub-system level requirements, threat assessments, and current technology assessments); actively support industry development of area avoidance systems by evaluating system integration and

operational use issues and methods with aircrew, aircraft systems, and airspace; develop and evaluate methods to determine aircraft as “hostile” or “friendly” in an effort to recognize the transfer of aircraft control from authorized crew to terrorists (comparison of aircrew activity to a baseline, biometric identification, unauthorized cockpit access during flight, etc.); and develop and evaluate usage of “threat assignment” into a secure system onboard, by other aircraft, and by ground agencies. Current research is focused on enhancing the onboard ground collision avoidance warning systems (e.g. Terrain Awareness and Warning Systems (TAWS)) to provide an input to the autopilot for actual collision avoidance. A key enabler to this research will be the timely and appropriate presentation of avoidance and system status information in the cockpit to authorized pilots. Work is progressing in establishing recommendations to improve the processes for disseminating Temporary Flight Restriction (TFR) information to the pilots in a timely manner, thereby reducing the likelihood of an unintentional blunder into restricted space.

V. Safe Aircraft Flight Recovery

The SAFR sub-project is newly initiated this year, and is meant to complement the work conducted in PAFS. SAFR addresses the recovery of the passengers by investigating concepts that, independent of on-board human actions, will safely land a seized aircraft at a secure site. The initial concept is a system that will recover an aircraft from a maneuver initiated by a hostile pilot, fly to a secure landing site, and safely land the aircraft, all within acceptable passenger ride qualities and without reducing safety or interfering with an authorized pilot’s control of the vehicle.

A feasibility study will be preformed which will examine all aspects of this system including issues with protected airspace and secure communications. This study will produce an initial ConOps, as well as a proposed approach for system development including the requirements and methods for initiating removal of control from a hostile pilot, recovery and landing, and establishing and using secure landing sites. The ConOps will also describe the interface to a protected asset flight system and ground systems. A survey of secure landing sites will document acceptable landing sites and their accessibility, including notification requirements. The final product is a Preliminary Design of aircraft and ground system interfaces, including concepts for secure CNS and vehicle interfaces, landing site locations, and interface to ground operations.

The goal of this sub-project is simple: develop the capability to safely recover a seized aircraft to landing at a secure site. While the goal statement is simple, the implications for goal success are extremely complex. In conjunction with PAFS, SAFR must recover the aircraft from a maneuver the hostile pilot has initiated, fly to a secure landing site, and safely land the aircraft without interfering with an authorized pilot’s control of the vehicle. The technology must also be developed to interface with both current and future aircraft capabilities. The SAFR sub-project intends to add a layer of protection that provides a “last line of defense” in protecting the aircraft, and in particular, those on board, against hostile intent.

VI. Electromagnetic Effects Surveillance and Detection

The goal of the EME sub-project is also to prevent aircraft from being used as weapons by protecting both air travelers and the general public from accidental or deliberate flight-path deviations caused either wholly or in part by Radio Frequency (RF) attack. Even though aircraft systems are certified against the negative effects of High Intensity Radiated Fields (HIRF), they may still be susceptible to RF attack. An RF attack is an unconventional attack, the effects of which are not readily apparent (such as the effects of an explosive or biological weapons attack), or well understood, as existing modeling and simulation capabilities are designed for nominal conditions. Furthermore, airports are also susceptible to RF attack, causing disruption, delays, and economic losses. Aircraft and airport RF surveillance and detection can provide an extra layer of security against these unconventional attacks.

A gap in US RF spectrum policy provides RF vulnerabilities in the restricted aircraft frequency bands. US spectrum policy is based upon a system of voluntary compliance, requesting that no unauthorized transmitters operate in aircraft frequency bands. However, potential terrorists will not consult spectrum policy before mounting an attack. The spectrum policy also encourages avionics manufacturers to design aircraft receivers with very low sensitivities to in-band, on-channel signals. These systems are so vulnerable to RF attack, it is possible to use commercial off-the-shelf (COTS) test equipment, etc. to “spoof” them.

Current Computational Electromagnetics Modeling (CEM) tools are of limited usefulness in the study of EM environment and its impact to aerospace systems. CEM research focuses on high fidelity techniques or coarse approximations, and little published work exists to develop techniques to bound the field strength or provide variable fidelity estimates with known precision. Current techniques use inefficient, brute-force methods to solve EM problems with prohibitively large and impractical memory requirements, requiring weeks or months of CPU time. New probabilistic approaches to bound and estimate the field levels are needed. Finally, certification of aircraft

for HIRF is often accomplished through expensive and time-consuming field tests. Certification through simulation would reduce certification costs, and would enhance manufacturer productivity by providing a virtual EM design environment. CEM probabilistic, statistical, Monte Carlo or topological techniques can be transformed into CEM HIRF certification tools.

The first objective of the EME sub-project was to perform an assessment of the potential risk of electromagnetic interference to aircraft communication and navigation radios due to covert and intentional, unauthorized RF transmitters, with a specific emphasis on security concerns of exploiting known interference issues for direct in-band, on-channel, localized RF attack on aircraft communication and navigation radios. To this end, a comprehensive RF vulnerability assessment has been conducted, identifying possible external and internal threat sources and targets. The EM threat to aircraft is primarily in the form of two different attack scenarios: a direct EM attack on the aircraft, or a covert EM attack involving the aircraft and the NAS. A direct EM attack could be considered to be a more "traditional" high power microwave (HPM) type of attack where a large, high power, and probably ground-based source is used to illuminate an aircraft on takeoff or landing. These EM sources would be custom made by terrorists out of commercially available components. A covert EM attack would be the avionics spoofing/jamming scenarios. Of most concern are the attacks on the NAS as no information, or false information from airplane transponders, can cause major problems for air traffic controllers. Furthermore, false localizer and glideslope information result in go-arounds, significant confusion, chaos, delays, and in the most extreme scenarios, accidents.

Now that the EM vulnerabilities are understood, the approach taken by the EME sub-project will be two fold: 1) develop advanced modeling and simulation techniques to predict RF propagation inside aircraft cabins and airports to aid in the development of requirements and technologies to protect aircraft radios, communications and navigation equipment against RF attack; and 2) develop technology, procedures, and implementation methods for integrated on-board and ground-based EM surveillance systems. Surveillance systems on the airplane would detect covert transmitters designed to jam or spoof either the transponder or other avionics equipment. Ground-based surveillance systems would detect and localize covert transmitters that may be designed to spoof or jam aircraft navigation or radio systems.

VII. Damage Adaptive Control System

Man-Portable Air-Defense System (MANPADS) missiles, have been identified as a significant security threat to commercial aircraft⁴. The effectiveness of shoulder-fired, surface-to-air missiles against military aircraft is well established. Recent events, however, have drawn increased attention to the threat that MANPADS may be used to bring down commercial airlines. It is estimated that there are thousands of MANPADS in circulation, and these weapons are becoming increasingly sophisticated with onboard logic to push away from the infrared (IR) target just before impact in order to broaden resulting damage and new features for countering active IR jamming and flare systems. Due to a maximum missile range of 20,000 feet, heavy commercial and military aircraft are susceptible to MANPADS during take-off and landing. In addition, proximity to the far-end of the runway during take-off increases the difficulty of recovering from damage. The long, lethal reach of these compact, man-carried weapons makes it very difficult to secure large areas surrounding civil airports from being used to direct attacks at arriving / departing aircraft. On-aircraft counter-measures have been developed for military aircraft to confuse missile guidance systems, but this technology is heavy, expensive, and not currently available for commercial aircraft. The goal of the DACS sub-project is to mitigate the in-flight safety and security risk of terrorist threats to the aircraft and public by improving survivability from vehicle damage brought about by MANPADS, onboard sabotage, anti-aircraft weapons, and other sources of malicious damage.

As seen in Figure 4, the DACS sub-project provides an integrated approach to MANPADS damage modeling, safety of flight assessment, and damage mitigation. Damage modeling requirements and data will be generated for aerodynamic properties, the engine, airframe, and vehicle components. Enhanced flight simulations and damage emulation will be developed using damage models and data. An assessment of MANPADS damage effects on aircraft safety of flight and recovery capability will be conducted, and will address such factors as the capability and probability of vehicle recovery with sustainable damage given the vehicle configuration, effects of damage, and flight scenarios. Enhanced flight simulations with damage models will be utilized. Technologies for MANPADS mitigation will be developed and include methods for damage detection and identification, adaptive control recovery and reconfiguration, adaptive engine control, and trajectory and landing site guidance. These technologies will be integrated and validated at NASA using analysis methods developed in parallel with the technologies, laboratory experiments in engine test facilities at Glenn Research Center (GRC), the Structures facilities at Langley Research Center (LaRC), piloted simulation facilities at Dryden Flight Research Center (DFRC), and the Systems and

Airframe Failure Emulation Testing and Integration (SAFETI) Laboratory at LaRC, and sub-scale flight tests at LaRC using the Airborne Subscale Transport Aircraft Research (AirSTAR) capability.

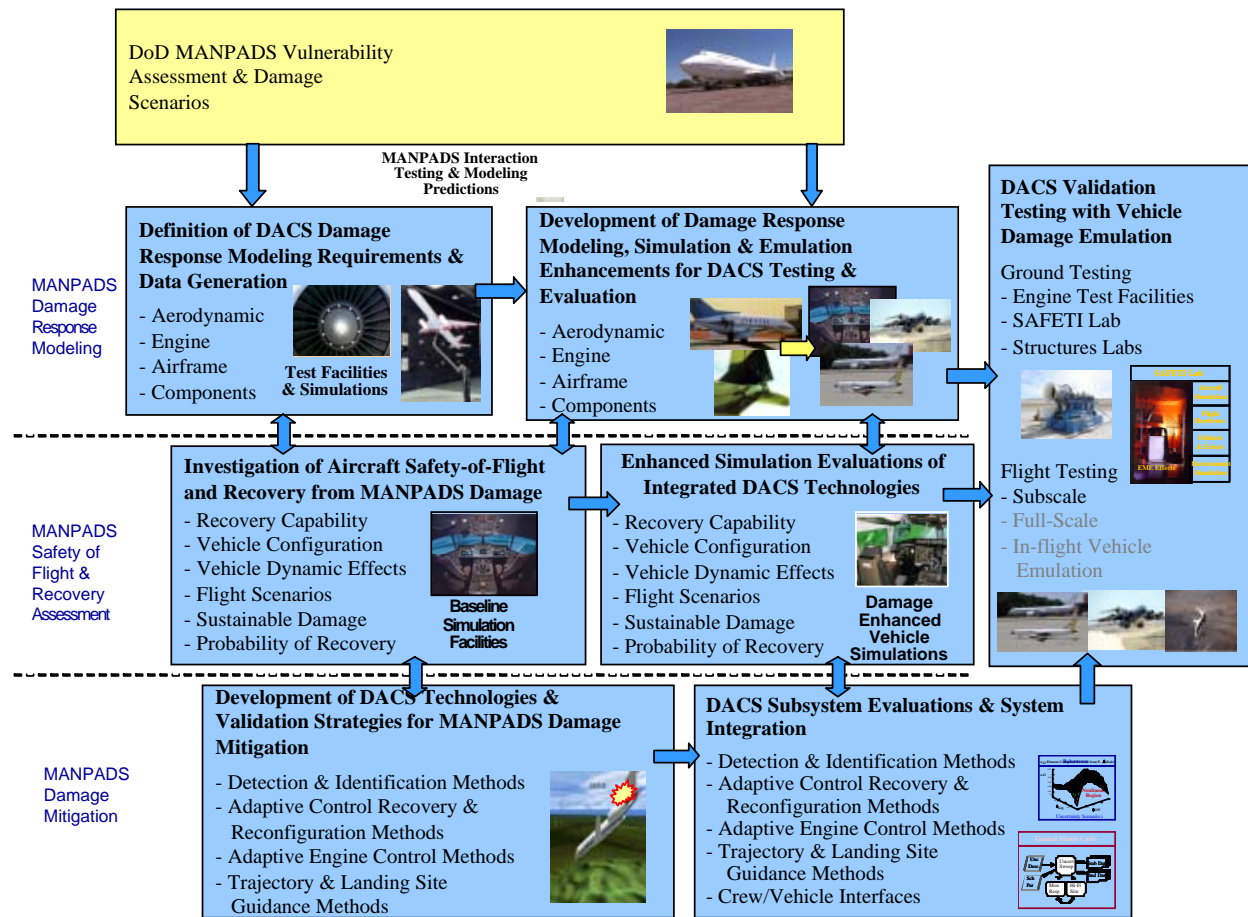


Figure 4. DACS Technical Approach

The objectives of the DACS sub-project are to advance the state of knowledge in the characterization and modeling of the effects of MANPADS-level aircraft damage including mathematical modeling, simulation, damage emulation for experimental testing, and safety of flight effects of vehicle configuration (flight scenario, impacts on handling qualities, probability of recovery) for the purpose of developing integrated damage adaptive control technologies including damage detection and identification, control recovery and reconfiguration, and trajectory and landing site guidance for in-flight damage accommodation and safe landing of the damaged vehicle.

A major challenge of the AvSSP will be delivering technologies applicable to the majority of current aircraft types. Based upon industry projections, at least 70% of the commercial transport aircraft in operation today will still be operating a decade from now. Affordability will also be a major implementation challenge given the inherent cost associated with the modification and retrofit of existing aircraft types. Consequently, major challenges driving the technical requirements for the DACS sub-project include the need for affordable, retrofitable systems and validation/certification methods to support timely commercial implementation of these systems. In addition, DACS technologies must be compatible with existing systems, and have flexible system integration capabilities to enable operators to customize the systems to meet their individual operational requirements.

A first step in developing characterization and modeling requirements for aircraft damage prediction is to estimate probable hit-point profiles of relevant transport aircraft based on their IR signatures. In a joint effort with the Air Force Research Lab (AFRL), an IR signature of NASA's Airborne Research Integrated Experiments System

(ARIES) commercial transport aircraft was collected, and is being used to determine likely hit-point profiles, which will in turn serve as the basis for the development of the most likely damage scenarios.

VIII. Fuel Tank Explosion Protection

The proliferation of MANPADS and small arms capable of bringing down an aircraft has already resulted in numerous shoot-downs and close calls involving civil passenger aircraft. The lethality of these weapons against large aircraft depends to a great extent on the ability to use the aircraft's fuel system against itself. That is, the weapons' moderate impact and explosion effects on large aircraft can be used to initiate a secondary explosion of the aircraft's fuel tanks, thereby magnifying the damage to a catastrophic level where flight cannot be maintained.

The FTEP sub-project seeks to enable adaptation of military heritage fuel tank inerting to commercial air transport aircraft to provide adequate protection within economic reach of commercial transport operations. To meet this objective, the FTEP sub-project will develop and deliver technologies that will counter the very large cost penalty that commercial flight operators would incur for adding fuel tank inerting to their aircraft, while still providing sufficient protection, including: flammability feed-back control and key components for advanced control of inerting systems; and design guidelines to assist designers with performing timely design, sizing, and aircraft integration of inerting systems matched to commercial air transport types. The FTEP sub-project will enable prevention of induced fuel tank explosion / fire on commercial transport aircraft arising from attack by MANPADS or small arms so that flight can continue to a safe landing.

Fuel tank inerting prevents fuel tank explosions by displacing most of the oxygen (O₂) in the tanks' open spaces with nitrogen to make the fuel vapors non-explosive. Insufficient O₂ available for combustion causes the initiation of the air/fuel explosion or fire to snuff out. Military aircraft have used inerting systems for some time, but their size, weight, and power needs make them unsuitable for application to commercial air transports. A commercial aircraft system to provide protection against MANPADS will need to be 3-5 times larger than current inerting systems due to the need to inert all fuel tanks on the aircraft (not just the center tank), and the requirement for increased displacement of O₂ over what is required to protect against accidental spark ignition. Recent evaluations conducted by the FAA's Technical Center found that reduction from the normal 21% to 12% was adequate for protection from accidental spark in jet fuel tanks⁵. The military uses 9.8% as the baseline for required O₂ reduction to protect aircraft against fuel tank secondary explosion arising from fragmentation and explosion of battlefield threats. To attain this level of protection, about twice the inerting system size is needed.

Improved flammability feedback and control holds promise for significantly reducing the amount of required inerting gas by distributing the gas only as needed. Current technology does not provide a means of detecting the flammability of each tank's ullage (gas in tank above the fuel level). Instead, inerting is based on feeding inerting gas per a fixed schedule to meet worst-case conditions. In addition, today's flammability reduction schedules are based only on reducing oxygen content in the tank ullage space, but ullage flammability is a combination of factors, such as oxygen / nitrogen ratio (an indicator of ability to arrest combustion) and oxygen/ hydrocarbon vapor ratio (an indicator of combustion strength). An improved control scheme using feedback of fuel tank flammability to continuously regulate inerting gas flow to the tanks according to their needs has the potential to allow significant reduction in inerting system size and bleed air penalties. Larger reductions, yet, are expected when feedback control is combined with the high efficiency air separation membranes used for generation of inerting gas that are now in development in the safety portion of the AvSSP.

Inerting system health monitoring from the cockpit is also enabled by flammability feedback and control. The measurement of flammability parameters in relation to inerting system output provides indications of system health that can be used to decrease maintenance costs. Indications of system degradation could be used to forecast impending failure to enable preventive maintenance action before a breakdown. Cockpit indications of tank inerting status could also give the flight crew a positive indication of adequate inerting protection before flight within potential reach of MANPADS and small arms.

An additional objective of the FTEP sub-project is to enable creation of design guidelines to assist designers with sizing inerting systems to commercial air transport designs. Commercial transport aircraft, designed without the military vulnerability hardening, will likely respond differently to battlefield threats. In addition, fuel tank geometries and internal designs vary greatly from aircraft to aircraft and can have a large impact on flammability. Military guidelines for applying fuel tank inerting will likely result in inadequate protection, or may add unnecessary weight, power consumption, and cost to commercial operation of the aircraft. The cycle for developing design guidelines will start with establishing a baseline of analyses and test techniques that can be used to address the case of civil transports against terrorist MANPADS and small arms threats followed by an estimate of threat effects and generation of preliminary design guidelines and concepts.

A literature study was performed to identify the inerting technology basis from which FTEP can base inerting improvements for commercial air transport operations. Disagreement regarding the lower limit of oxygen concentration needed to produce an inert condition exists. Most testing indicates depletion to about 12% O₂ is needed, but the current military standard remains at 9.8%, requiring significantly a larger inerting system. To date, testing has focused only on the infrequent worst-case of fuel /air mixture. However, fuel tank flammability state is most often lean or rich, requiring less depletion of O₂ by a smaller inerting system. The FTEP sub-project will continue testing to better define the flammability parameters of civil transport aircraft. Simultaneously, the FTEP sub-project will develop fuel tank sensors to measure fuel flammability state during flight, along with analytic flammability models and control algorithms to enable inerting systems that can actively respond to changes in flammability state.

IX. Fire Resistant Damage Tolerant Composites

When an explosion occurs on an airplane regardless of its origin (explosion in the fuselage or cargo bay or as a result of a missile strike), the damage that occurs to the airplane structure could result in the loss of the vehicle. Furthermore, carbon fibers (principle reinforcement for composites) are electrically conductive and can cause considerable damage to electrical equipment of all types (computers, communications, radar, guidance systems, etc.) when released into the atmosphere during a fire. The objective FRDTC sub-project research is to develop affordable, light-weight, fire-resistant, composite structures with unparalleled high-energy damage tolerance.

It is unlikely that prevention techniques can eliminate all hostile acts such as the detonation of explosives on board aircraft and strikes by MANPADS or shoulder launched missiles, therefore materials and structures technology must be developed to mitigate the effects of damage from such acts, thereby providing a safer and more secure environment to air travelers. The use of exterior composite structures on commercial aircraft is increasing because of the many advantages composites offer over metallic structures. More than 50% of the structural weight of the new Boeing 787 is proposed to be composites. The new Airbus A380 will have more than 20% of the structural weight in composites. The Airbus A320 has composite structures in parts of the wing, fuselage and empennage. Use of composite structures in general aviation aircraft is increasing as well. The aircraft fuselage structure should provide support adequate loading in the presence of initial explosive-induced damage (which typically involves a high-pressure pulse loading followed by fragment penetration), and under this load, the damage should not propagate to levels that can result in catastrophic structural failures. No economically viable, light-weight composite fuselage structures are available today that offer the proper level of damage tolerance.

The specific performance goal of the FRDTC sub-project is to develop composite structures technology for use on commercial and general aviation aircraft that will mitigate the effects of hostile acts such as explosives detonated on board an airplane or strikes by shoulder launched missiles. A two-pronged approach will be pursued to meet this goal: 1) develop fire resistant resin matrices and their composites with the proper combination of properties required for use on exterior structures of commercial airplanes; and 2) develop composites having resistance to high-energy impact damage such as that emanating from an explosion.

In preliminary studies, laminates from two formulations containing phosphorus performed well in a 60-second vertical burn test with 0-second self-extinguishing times (15 seconds is acceptable) and 2.8-inches of burn length (6 inches is acceptable). Future work will be directed towards optimizing the formulations containing phosphorus to improve handleability, laminate performance and fire retardancy. The initial efforts in the damage tolerant element of the FRDTC sub-project is focused on developing the analysis tools to better understand and characterize damage dynamics. The tools will be used to predict damage growth, and will be validated against existing experimental data. The materials and structures products delivered by this sub-project are envisioned to be available for next generation commercial and general aviation applications.

X. Summary

A primary goal of NASA's Aviation Research Mission Directorate is to enable a safer and more secure air transportation system by reducing vulnerability to hostile threats, and mitigating the consequences hostile acts. By 2009, NASA has pledged to develop and transfer technologies that will reduce the vulnerability exposure of aircraft, as well as reduce the vulnerabilities of other components in the air transportation system. The Aircraft & Systems Vulnerability Mitigation Project of the Aviation Safety and Security Program intends to support NASA is this goal

by delivering technologies and methods which will reduce the vulnerability of aircraft to threats or hostile actions by detecting and mitigating the consequences to the aircraft from an intentional attack.

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